Title:
Large earthquakes in the Tokyo area

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Large earthquakes in the Tokyo area

An interim report on
a Swiss Re-sponsored study

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Summary

The first official probabilistic earthquake hazard assessment for Japan was released in March 2005 in a milestone study initiated by the Japanese government. A group of scientists from the AIST[1], NIED[2], GSI[3], JMA[4] (Japan) and the USGS[5] (USA), sponsored by Swiss Re, embraced the challenge and took it one step further. The Japanese-US team zoomed into the highly exposed Greater Tokyo area and exhaustively analysed the unmatched wealth of scientific and historical data available for this region.

The Swiss Re-sponsored study estimates that the overall likelihood for intensity-6 (JMA intensity scale) or greater shaking in Tokyo, Kawasaki, and Yokohama for the next 30 years is in the preliminary range of 35%–40%. The research has also found that while a recurrence of the great 1923 Kanto earthquake was less likely than previously thought, earthquakes similar to the 1855 Ansei-Edo event are larger and more common than previously assumed. Although both events cause JMA intensity-6 (severe) shaking in Tokyo and Yokohama, the Ansei-Edo type event drives the combined probabilities, thus becoming the dominant factor in Tokyo's hazard landscape in the next 30 years. Even though these results are based on different methods and data evaluations than the governmental study used, they still concur with it well in both qualitative and quantitative terms.

Based on the wealth of new insights, Swiss Re will review – and possibly update – its own earthquake risk assessment model, so that latest scientific progress is properly reflected. This review will be based on published results from both the government- and the Swiss Re-sponsored studies. We encourage the other insurance industry players to analyse these research results and weigh the potential impact and implications they might have.

[1] National Institute of Advanced Industrial and Science Technology, www.aist.go.jp/
[2] National Research Institute for Earth Science and Disaster Prevention, www.bosai.go.jp/
[3] Geographical Survey Institute, www.gsi.go.jp/index.html
[4] Japanese Meteorological Agency, www.jma.go.jp/JMA_HP/jma/index.html
[5] United States Geological Survey, www.usgs.gov/

Introduction

Far from civilization, earthquakes might be regarded as natural phenomena which reflect the dynamics of Earth, but close to densely populated and highly civilized areas, they are nothing less than an existential threat to life and property. The Greater Tokyo area, in particular, has an enormous concentration of population, property and infrastructure perched above active geological features, exposing it to an extraordinary and, unfortunately, hazardous situation. A recently published article, which refers to the governmental study (IHT/Asahi, 26 February 2005[6]) analysed the potential economic impact of a major earthquake hitting Tokyo. Its conclusion: the economy will face a loss of some JPY 112 trillion (about USD 1 000 billion), split into JPY 67 trillion for repair and JPY 45 trillion for business interruption. These astronomical figures dwarf previously experienced losses and spur the insurance industry to ask: Are we ready to cope with the "big one"?

To gain a certain degree of control over this situation, society gathers as much information and knowledge about earthquakes as possible, trying to answer questions such as *where, why* and *how often* do they occur. Based on this understanding, mitigation measures are taken to minimise the impact of possible catastrophes. While earth scientists can give satisfactory answers to the *where* and *why*, the question *how often* specific earthquakes occur is, on the other hand, far more complex and often remains unanswered. Here, only a concentrated scientific effort can reveal the details necessary to determine event probabilities, which, in turn, are essential for a successful probabilistic risk analysis.

Such event probabilities are of greatest interest in highly exposed areas such as Greater Tokyo, as they bear a key influence on the outcome of any earthquake risk assessment for Japan. Given that, Swiss Re decided to commission an international research effort for the Greater Tokyo area with Japanese and US earth scientists, lead by Shinji Toda of the AIST Active Fault Research Centre and Ross Stein of the USGS Earthquake Hazards Team. The scientific objective of this study was to develop a comprehensive description and understanding of earthquake occurrence in Greater Tokyo, the goal being to derive probability forecasts for major earthquakes striking the region in the years to come. Achieving this goal relied on a unique collaborative effort by combining specific Japanese research methods with US-expertise in advanced stress-transfer calculations. The latter have already been applied successfully for California and other seismicity-prone regions of the world, such as Turkey.

Swiss Re is interested in expanding knowledge for its own risk assessment. Since the company also wants the general public and the insurance industry to derive benefit, however, all results will be published in scientific journals. Moreover, selected results are available already now on the internet[7]. The technical paper in hand provides first-hand, newly gathered information on historical events, their observed shaking intensity and newly determined (preliminary) earthquake probabilities. Further, it identifies future sources of possible catastrophic quakes that threaten Tokyo and its surroundings. All this information is public, so that many applications – from civil protection agencies to building code developers and complex risk assessment models used in the insurance industry – can benefit equally.

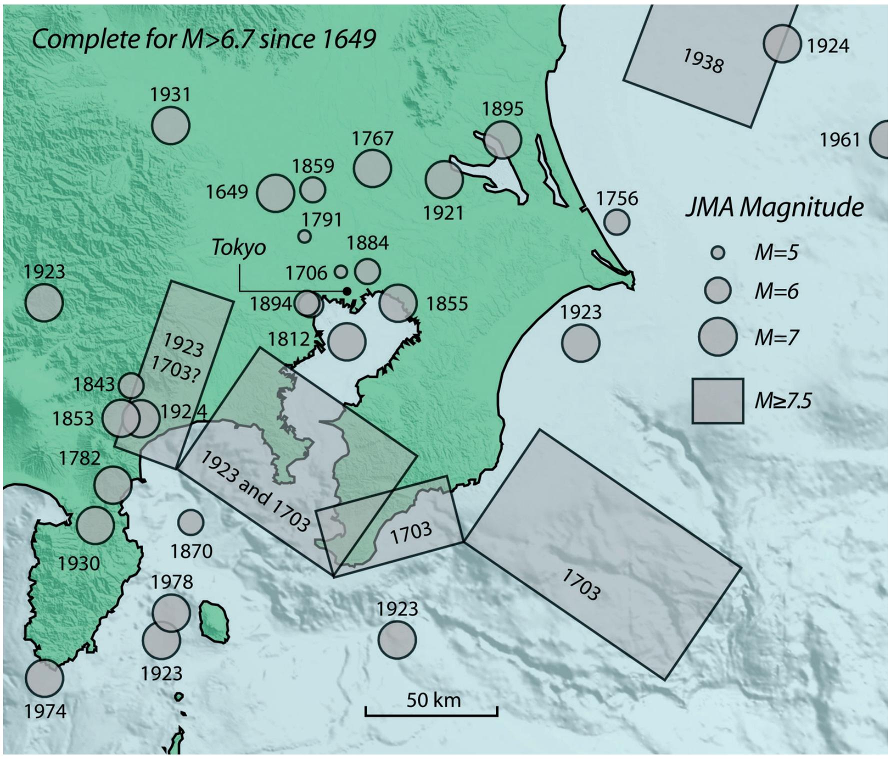
[6] International Herald Tribune/The Ashai Shimbun, www.asahi.com/english/
[7] quake.usgs.gov/~tokyo

Swiss Re-supported earthquake study on the Tokyo area

Background
Figure 1 shows the epicentres of large earthquakes that shook Tokyo in the past 400 years. During this period, violent shaking (JMA 6 or greater) in Tokyo was caused by three destructive earthquakes. The largest of the events (Genroku earthquake) occurred in 1703 with M~8.2. In 1855, the Ansei-Edo earthquake in the North Bay Area hit Tokyo with an estimated M~7.2. Finally, the most recent and most studied Kanto event, the 1923 Taisho M~7.9 earthquake, left Tokyo with tremendous destruction after violent shaking and subsequent fires. How likely is it that Tokyo will suffer major earthquake damage in the near future? The particularly complex tectonic environment of the Greater Tokyo area makes this a truly challenging question. Nevertheless, the combination of great societal significance, unparalleled modern data, and rich historical record were an excellent starting point for the research team to further investigate the Tokyo specific hazard.

Wherever possible, the research team relied on observations rather than models or expectations to build their analysis. The modern seismic (1926–2005) and geodetic (1990–2005) record, the historical earthquake record (1600–1923), and the prehistoric earthquake record (past 7 200 years) are the principal data sets used in the Swiss Re-sponsored study. The main elements for the earthquake probability estimates are:
- new analyses of the 1703 Genroku, 1855 Ansei-Edo, 1923 Kanto earthquakes
- a new analysis of the distribution of strain accumulation and
- a new analysis of the some 10 000 observations of shaking in Kanto over the past 400 years.

Figure 1:
Epicentres of the large earthquakes that shook Tokyo in the past 400 years (E. Grunewald, 2005; W. Bakun, 2005; T. Usami, 2003, N. Hamada et al, 2001).



Kanto's earthquake history
Assessing the probability for future large earthquakes relies on a robust and in-depth analysis of historical and prehistorical seismic data. Japan provides one of the richest earthquake datasets in the world, including instrumental records, a modern seismic catalogue and thousands of accounts of effects of historical earthquakes.

The team of Japanese-US scientists re-interpreted the 400-year long earthquake catalogue (AD 1600–2003 for M >= 6.75). The location and magnitude of historical earthquakes were determined from observed intensity data using a computer algorithm that had been successfully applied already to other regions (eg California, Turkey, France, and Italy) and adapted to the complex tectonic environment of the Tokyo region (W. Bakun, J. Geophys. Res, 2005). This study provides an objective estimate of the magnitude, depth and location of the Ansei-Edo 1855 earthquake (see Figure 1) which, together with the Sagami trough earthquake type, is key to understanding the seismic landscape around Tokyo. The team inferred that the 1855 Ansei-Edo event was a M=7.2 shock located at a depth of 30–60 km at the north end of Tokyo Bay, probably beneath Chiba. This magnitude is larger than previously assumed. The earthquake struck at the southern end of an active seismic corridor beneath the Kanto plain. This seismic source produced numerous M≥6 shocks during the 75 years before the 1923 Kanto earthquake and is also highly active today, with shocks smaller than M=6, however.

While we do not know enough about prehistoric shocks similar to the 1855 Ansei-Edo-type event, paleoseismic data in the Tokyo Bay provides a 7 200 year record of past, major Sagami trough earthquakes similar to the 1703 Genroku and 1923 Taisho events. (M. Shishikura, 2003) Beaches on the Boso peninsula are uplifted by approximately 1 m during each M~8 earthquake on the nearby Sagami trough. The similar uplift for each event indicates that the size and location of these prehistoric earthquakes must have been quite similar. Estimated dates of 19 uplift events yield a mean event interval time of 375–600 years for Taisho events, some 50% less frequent than previously assumed. The short 220-year time span between the 1703 and 1923 events is rather unusual; such frequency has only happened twice in 7 200 years. The team also concluded that these great events are neither periodic nor random in occurrence, but fall somewhere in between these two extremes. The earthquakes are less periodic than was supposed by many researchers, but they are nevertheless more regular than the well studied great earthquakes on the San Andreas fault in California. About every 2 000 years, a longer fault line rupture occurs, extending farther to the east; these Genroku events are considerably larger (M~8.2) and are often associated with tsunami deposits.

Earthquake probability models
Among the different ways to describe earthquake occurrence probabilities, the purely *time-independent (Poisson)* approach assumes that the probability of a future event is independent of the locations and time of previous events. Earthquakes are thus assumed to have no "memory" and to happen randomly. Another related approach (again time-independent and Poisson-driven) describes the long-term behaviour, over which earthquake occurrences will average out. In other words, while this may not be the best estimate for a given time period ahead (say the next 30 years, a typically used value), it is nevertheless the best estimate of the average for this given time range behaviour. For the present study, the latter approach was chosen.

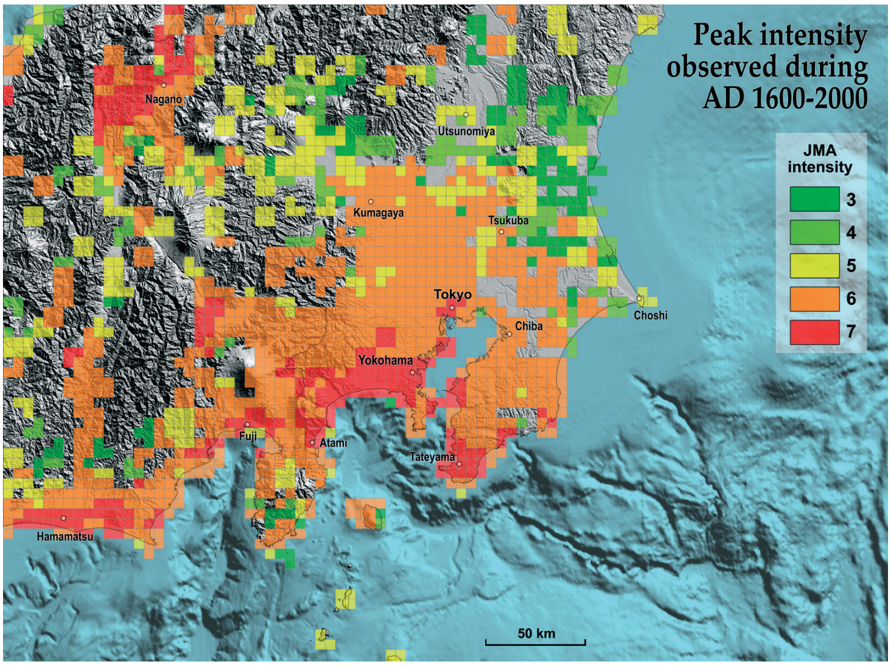
A completely different model, on the other hand, for determining earthquake recurrence probabilities is the *time-dependent* methodology, which takes into account the time interval since the last earthquake on a given fault. The probability of an event occurring in the future grows with the elapsed time since the last event. The basic assumption of this approach is good knowledge of the event interval and its periodicity.

The Poisson model relies on fewer assumptions than time-dependent modelling and so is most reliable when data is sparse for large events, which is typically the case for small and moderate magnitude earthquake activity. For larger magnitude events, the assumption of independent occurrence can be tested against a long earthquake record. As for the present situation of Tokyo, both, time-independent and time-dependent methods were applied (see *Results and conclusion* on p. 8 for details).

Kanto's peak intensity observations
The 400-year long historical catalogue of 10 000 felt effects compiled, digitised, and interpreted by the Japanese-US scientists provides a powerful independent assessment of Poisson probability of strong shaking in Tokyo. Figure 2 shows the maximum values of JMA intensity experienced in the past 400 years in the Greater Tokyo region. The spatially-weighted peak intensity is plotted in 1 800 5 x 5 km cells. The map immediately highlights areas that experienced strong and violent ground shaking due both to proximity to earthquake sources and to local soil conditions.

This comprehensive four-century record encompasses a very wide range of seismic behaviour of Kanto, providing an invaluable Poisson probabilistic forecast for shaking during any time interval or intensity level. Three attributes make working directly with the observed intensities invaluable: First, one does not need to locate or determine the magnitude of any earthquake. Second, site amplification is naturally incorporated into the observations, rather than artificially introduced later by modelling. And third, the most reliable intensity data comes from the most densely populated and longest-inhabited regions, precisely those sites where most of the buildings are concentrated and where insurance is purchased.

Figure 2:
Peak intensity observed during AD 1600–2000
Note: Intensities are given in JMA scale. JMA intensity 6 translates into intensity levels IX to X on the Modified Mercalli Scale. (S. Bozkurt et al, in prep., 2005; based on data from T. Usami, 1994, 2003; N. Hamada et al, 2001; Moroi & Takemura, 2002; JMA, 2004).



Kanto's earthquake future
The earthquake catalogue spanning 400 years of moderate and large events and 7 200 years of great Sagami trough earthquakes (1923 and 1703-type) provides the framework to the Kanto earthquake probability model. The next step is to identify the sources for future shocks. The complex tectonic configuration beneath Kanto – with its three plates in collision and with some of the plates torn, highly deformed, or broken into smaller pieces – presents special challenges. The team had to fully understand this "3D puzzle" to develop a reliable probability model.

Supported by new plate motion datasets and modelling expertise, the team developed a new plate Kanto model, new source models for the 1923 and 1703 earthquakes (Nyst et al and Pollitz et al, in press, J. Gephys. Res.), and a new model to identify faults on which strain is accumulating (Nishimura and Sagiya, to be submitted to J. Geophys. Res.). With these tools, they identified the most likely sources for future events. Figure 3 shows the areas capable of generating great earthquakes in the pink-shaded regions (such as the 1923 M=7.9 and M=8.2 1703 shocks, and one of roughly similar size located farther offshore in 1677) and the area, in a green-shaded region, where moderate and larger future earthquakes (1855-type with M<7.4) can be generated.

While the 1923 and 1703 sources are confidently modelled and identified, there is still some ambiguity on the 1855 source at the north end of Tokyo Bay. Nevertheless, the proximity of this large earthquake to Tokyo and its vigorous seismic record (with only slightly smaller shocks in 1812 and 1884) identify this region as a major threat of strong shaking to Tokyo.

Why, then, have large earthquakes deserted this seismic corridor since 1923? The use of a time dependent probability model – where earthquake occurrence influences future seismicity nearby – provides the best answer. By applying cutting-edge stress transfer calculations, the team of Japanese-US scientists (Toda and Stein, J. Geophys. Res., 2003; Toda et al 2005; Stein and Toda, Nikkei Science, 2003) determined that the 1923 earthquake caused a "stress-shadow" around Tokyo in the Northern Tokyo Bay region where the 1855 earthquake source was identified (Figure 3). This shadow effect means that the stress build-up has been slowed down, with the consequence of temporarily reducing the seismic activity. However, now more than 80 years since the 1923 event, this shadow is thought to be diminishing and the reconsideration of the earthquake potential of the seismic corridor extending north from Tokyo bay (see green-shaded area in Figure 3) is taking on critical importance in quantification of seismic hazard in Tokyo.

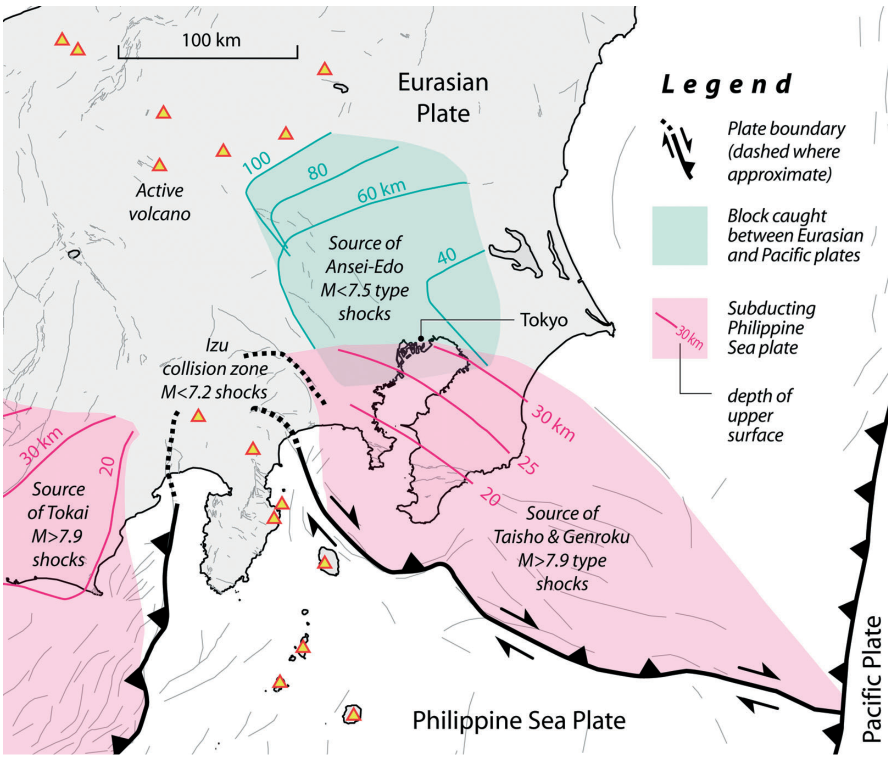


Figure 3:
Areas with capability to generate great earthquakes around Tokyo (S. Toda & R. Stein, in prep).

Results and conclusion[8]

The revised historical catalogue allowed the team to derive quite robust estimates of earthquake occurrence frequency as a function of magnitude, providing the basis for building a *time-independent (Poisson)* probability model (see box on p. 5 for a short methodological description). For Ansei-Edo type events, this probability is about 35% in 30 years, based on the rate of M≥2 shocks since 1979. For Taisho-Genroku type events, the Poisson probability is about 7% to 9% in the next 30 years, based on the record of 19–21 events during the past 7 200 years.

Using powerful new analytical methods (*Parsons*, J. Geophys. Res, 2005), the study derived a much longer event interval but a much larger aperiodicity (or irregularity) for the Sagami trough earthquake type than other recent studies. The longer event interval lowers the probability for the next 30 years, since only about 20% of the average 475-year event interval has elapsed since the 1923 event. The more irregular occurrence spreads out the probability, however, so that already soon after the last great shock, there is some likelihood of another one. These two factors tend to offset each other, yielding a low <0.5% *time-dependent probability* of a Taisho (Sagami trough) event for the next 30 years. Since the event interval for Taisho-type events is about 475 years and only 80 years have elapsed, the time-dependent probability is lower than the Poisson probability. A time-dependent probability for the Ansei-Edo earthquakes is much harder to estimate, because such deep earthquakes leave no prehistoric record. The most one can say is that a time-dependent probability for such M~7.2 events striking close to Tokyo is probably higher than their 35% (time-independent) Poisson probability. This, mainly because the 150-year elapsed time is long compared to the estimated average event interval of about 200–300 years. Based on an assumed 75 mm/year of plate motion quite some stress or in other words plate movement potential has built up since the last major shock.

Risk assessment for the Japanese insurance industry depends heavily on the quantification of probability of strong shaking in Tokyo. The probability of strong shaking (JMA Intensity 6 and larger) estimated by the Swiss Re-sponsored study for Greater Tokyo is reported in Table 1.

Table 1:
The time-independent probability of strong shaking in the next 30 years in Tokyo is about 40%, to which the main contributors are 1855 Ansei-Edo-type earthquakes (with 30 year 35% probability). The 1923–1703 Taisho-Genroku-type events contribute to the 30-year time-independent probability only with 7% to 9%. However, the probability of Taisho-Genroku-type events substantially decreases if the time-dependent approach is applied. Note: all reported probabilities are preliminary and subject to scientific review.

Earthquake type	**Time-independent**	**Time-dependent**	**Governmental study (Earthquake research committee, 2005)**
Ansei-Edo (1855) (M~7.2)	35% in 30 years	n.a. (>35% assumed)*	70% in 30 yr for M>6.7 over a larger region***
Taisho-Genroku (1923) (M~7.9 to M~8.2)	7%–9% in 30 years	< 0.5%	< 0.8%
Combination	about 40% in 30 years	35% in 30 years**	70% in 30 years***

* Based on time elapsed since last event (150 years), the constellation points to a deficit in plate movement

** Combination of time-independent (Ansei-Edo) and time-dependent (Taisho-Genroku) information

*** The hazard region of the Ansei-Edo type events in this and the governmental study differ considerably. The latter refers to a larger area, resulting in higher probabilities of an earthquake occurring.

[8] Note: All reported event probabilities are preliminary and subject to scientific review.

The probability results are definitely shifting the focus of hazard assessment for Tokyo from 1923 M~8 Taisho-type events to 1855 Ansei-Edo-type (M~7.2) earthquakes. The high damage potential from the latter events stems from both those events' frequency and their proximity to Tokyo. In the next 30 years, 1923 Taisho-type events will play a relatively smaller role in the hazard landscape of Tokyo. To our best judgment, the likelihood of a Taisho type event is <9% in 30 years. Combining the ~35% probability for Ansei-Edo type events, the overall likelihood for JMA-intensity-6 or greater shaking in Tokyo, Kawasaki, and Yokohama for the next 30 years is about 40%.

The Swiss Re-sponsored scientists stress that these results are probabilities, and still reflect many uncertainties. By the same token, however, the study draws on state-of-the-art methodology and specialist knowledge. The extensive new datasets this study has produced and now offers to the community will provide lasting value and hopefully inspire others to carry out further investigations.

Looking ahead

In a short period of just a couple months, a wealth of new, thoroughly researched findings relating to the earthquake hazard in Japan has been published. All these findings measurably help to narrow the uncertainty surrounding probability estimates for large earthquakes shaking Japan, and for the Greater Tokyo area in particular. As is typical of risk assessment science, probability assessments are associated with considerable uncertainty and results can deviate largely from one study group to the other. In the present case, however, the situation is unique; while using a different team of earth scientists, data sets and analysis methods, the findings concur with one another. Both study groups, the governmental commissioned group, as well as the Swiss Re-sponsored study group, point to the same fact: in the current seismic setting, the city of Tokyo is far more at risk by Ansei Edo-type earthquake activity at somewhat lower magnitudes than by the Kanto-type activity at higher magnitudes.

However, the work hardly finishes with the presentation and acceptance of scientific results. For us at Swiss Re they rather mark the starting point. The Kanto-type earthquake has typically dominated risk assessments for insurance purposes so far. As a next step, Swiss Re will re-analyse the seismic hazard components of its risk assessment model for all Japan, focusing particularly on the Greater Tokyo area, and based on the wealth of new insights relating to occurrence probabilities and resulting shaking hazard patterns. This review will draw on published results from both the government- and Swiss Re-sponsored studies.

Probabilistic risk assessments do not save human lives per se. They do, however, influence risk perception and enable the public to take risk mitigation measures to minimise the impact of a major event. By enabling probability research for earthquake in the Greater Tokyo area, Swiss Re contributes to the ongoing risk dialogue, while also developing a more precise picture on one of the reinsurance industry's top nat cat exposures.

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